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A DAMAGE MECHANICS SOURCE MODEL FOR UNDERGROUND NUCLEAR EXPLOSIONS

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13. ABSTRACT (*Maximum 200 words*)
Recent advances in the damage mechanics of brittle solids have made it possible to calculate stress-strain curves for the non-linear source regime of underground nuclear explosions where the rock is being actively fractured. It has been shown that the damage-based rheology can explain the anomalously broad source pulses observed in the free field of explosions in granite. It also offers a physical explanation for why such pulse broadening was not observed in laboratory experiments in terms of the scaling of rock strength with the size of preexisting fractures. In this report we discuss how damage mechanics may be used to modify the Mueller-Murphy source model to explicitly include the fracture distribution in the explacement medium thereby providing a physical interpretation of source parameters which specifiy the width of the pressure pulse at the elastic radius, and the elastic radius itself. These parameters are currently evaluated empirically using calibration shots of known yield for each site. The resultant improvement of our understanding of the relation between the source medium and seismic coupling at high frequencies is especially important in view of the recent trend toward the use of higher frequency regional phases for yield estimation and discrimination allowed by improved seismic accessibility to test sites.

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INTRODUCTION

Current seismic yield estimates are based on scaling laws which relate the seismic source spectrum to the yield and depth of burial (Mueller and Murphy, 1971; Helmberger and Hadley, 1981; von Seggern and Blandford, 1972). Since these scaling laws do not contain any physics relating to the inelastic source regime, they must be calibrated for each site using shots of known yield to fit source parameters. However, there is reason to expect that the source parameters in such scaling laws are especially sensitive to the pre-shot fracture spectrum in the source emplacement rock. Non-linear processes like crack growth and amplitude dependent attenuation are known to depend on the density and length distribution of preexisting cracks. By implication, both the size of the elastic radius and the pulse shape at that radius should depend on the fracture spectrum. The ultimate goal of the research reported below is to formulate a source function with parameters which can be determined from measurable physical parameters of the source rock such as velocity, density, porosity, initial fracture spectrum, and degree of water saturation. Such a scaling law would allow more accurate corrections for variations in the emplacement medium without requiring extensive calibration shots.

There is observational evidence that the source function is sensitive to the fracture spectrum in the emplacement medium. Rimer et al. (1987) performed numerical calculations of the particle velocity measured in the free field for underground tests in granite. Using laboratory data for rock strength, they were unable to predict pulse-width successfully. In order to make the models correspond to the field data, much lower fracture strength than those in the lab were required. Sammis (1989) offered the explanation that the weaker rheology was the direct result of larger fractures in the field. More recently, McEvilly and Johnson (1989) have measured the seismic radiation from a series of chemical explosions as a function of depth in a limestone quarry. As illustrated in Fig. 1, they observed a pronounced shift toward higher frequencies as the depth of burial increased. We hypothesize that this is due to the suppression of crack nucleation and

growth with confining pressure. In a recent review of source models and scaling laws, Denny and Johnson (1991) conclude that the cavity radius, the seismic moment and the corner frequency of explosions are all dependent on the depth of burial. They reference Larson's (1984) work which suggests that these effects may result from the increase in shear strength with depth. Indeed, since shear failure in the damage mechanics model is a simple consequence of the growth of fracture damage to a critical level (where the stress-strain curve becomes unstable) the suppression of crack growth by confining pressure is equivalent to an increase in shear strength with depth.

If the nucleation and growth of fractures in the non-linear source regime can significantly broaden the source pulse and change the elastic radius, then the process may significantly reduce the radiation of seismic waves at the high-frequency end of the seismic spectrum. This is especially significant since recent yield verification and source discrimination schemes increasingly utilize higher frequency local phases as the joint verification program has allowed more local seismic monitoring. The spectrum of initial fracture sizes at a test site may turn out to be as important as emplacement rock type in determining the yield from seismic radiation.

SEISMIC SOURCE FUNCTIONS

The uncertainty in seismic yield determination can be broken down into uncertainties associated with the propagation of the seismic waves and uncertainties associated with the source coupling. The recent use of high-frequency local phases such as L_g (see e.g. Ringdal, 1990) has significantly reduced uncertainties associated with propagation, but our understanding of the effects of the emplacement medium on seismic coupling has not significantly improved since the 1971 work of Mueller and Murphy.

The Mueller-Murphy source assumes a step function followed by an exponential decay of the pressure source which acts on a spherical surface at the "elastic radius" r_{el}.

$$p(t) = \left(p_o e^{-\alpha t} + p_{oc}\right) H(t) \tag{1}$$

This time function was chosen because it mimics near-field velocity records. The elastic radius is chosen such that it contains all the non-linear source phenomena; the medium is assumed to be perfectly elastic for $r > r_{el}$.

The elastic radius is defined by the assumption that the peak stress, p_{os}, at the elastic radius is a fixed fraction of the overburden pressure at the depth of burial h.

$$p_{os} = 1.5\,\rho g h \tag{2}$$

The peak shock pressure in the non-linear regime is assumed to be of the form

$$p_s = \frac{AW^m}{r^n}\,. \tag{3}$$

They further assume that n is independent of the emplacement medium and m = n/3, so the final scaling relation is

$$\frac{r_{el_1}}{r_{el_2}} = \left(\frac{A_1}{A_2}\right)^{1/n} \left(\frac{W_1}{W_2}\right)^{1/3} \left(\frac{p_{os2}}{p_{os1}}\right)^{1/n} \tag{4}$$

which, when the explosions are in the same medium, reduces to

$$\frac{r_{el_1}}{r_{el_2}} = \left(\frac{W_1}{W_2}\right)^{1/3} \left(\frac{h_2}{h_1}\right)^{1/n} \tag{5}$$

P wave amplitude spectra in the far-field were used to determine the empirical constants: n = 2.4, $A_{salt}/A_{t\text{-}r} = 12$, $A_{shale}/A_{t\text{-}r} = 5.3$, and $A_{vt}/A_{t\text{-}r} = 0.23$ (where subscripts t-r = tuff-rhyolite and vt = volcanic tuff). The constant α in equation (1) is assumed to be of the form

$$\alpha = k\left(\frac{c}{r_{el}}\right) \tag{6}$$

where c is the p-wave velocity and k depends on the source rock: for tuff, k = 1.5; rhyolite, k = 2.0; shale, k = 2.4; and salt, k = 4.5. The broad pulses observed in granite imply a very small k, which suggests that k may reflect the fracture structure as well as the porosity. Using our damage mechanics model, it should be possible to relate k to the initial damage spectrum.

Hence, the Mueller-Murphy source makes a number of reasonable assumptions about the source, and then uses calibration shots to fix the values of the media dependent parameters A, n, and k. One objective of the work described below is to use recent developments in the damage mechanics of brittle solids to make a physical interpretation of the coupling parameters of the Mueller-Murphy source model in terms of physical, measurable, properties of the source emplacement medium, thereby eliminating the need for calibration shots at each new site, and allowing an estimate of the variation in the source function as a function of geological setting at a given test site.

To help focus the discussion, consider the schematic diagram of buried explosive source shown in Fig. 2a. For our purposes, we simplify the source and identify three non-linear regimes as indicated in Fig. 2b: the "hydrodynamic regime" in which rock flows, the "damage regime" in which the rock behaves as a solid but stresses are large enough to extend existing cracks, and the non-linear attenuation regime (not shown in 2a) in which stresses are large enough to produce amplitude dependent attenuation by motion on preexisting fractures but not sufficiently large to cause additional fracture. The hydrodynamic radius, r_h, depends on the equation of state of the emplacement medium and is the subject of high pressure shock wave studies. The damage radius, r_d, is defined by the condition that the peak radial stress has fallen to a level which is just sufficient to nucleate fractures from initial flaws in the emplacement medium.

The damage mechanics developed by Ashby and Sammis (1990) allows a quantitative evaluation of r_d. Their equation for the radial stress σ_r required to initiate flaws when the hoop stress is σ_θ is

$$\sigma_r = \sigma_o + c_1\sigma_\theta \qquad (7)$$

where c_1 depends on the coefficient of friction μ on the starter flaws

$$c_1 = \frac{\sqrt{1+\mu^2} + \mu}{\sqrt{1+\mu^2} - \mu}$$

The other constant σ_0 is defined as

$$\sigma_o = \frac{\sqrt{3}}{\sqrt{1+\mu^2} - \mu}\left(\frac{K_{1c}}{\sqrt{\pi a}}\right)$$

where K_{1c} is the critical stress intensity factor for tensile failure and a is the half-length of the largest initial flaws in the emplacement medium.

It is important to note that the damage radius is not simply a function of rock-type. In fact, the parameters K_{1c} and μ are almost independent of rock type. Rather, r_d is most sensitive to the size of the largest flaws in the emplacement medium. The effects of ground water saturation is to reduce the effective μ on pre-existing cracks thereby increasing r_d. Note that eqn. (7) is of the form assumed by Mueller and Murphy (1971) (eqn.2 above) as long as the depth of burial is great enough that $c_1\sigma_\theta >> \sigma_o$.

The elastic radius r_{el} is more difficult to define because there is no physical cutoff to the non-linear attenuation. However, if amplitude dependent attenuation is due to motion on pre-existing flaws, than r_{el} can be expected to scale with flaw-size in a similar wav as the damage radius since a smaller stress is required to produce motion on a larger fracture. In fact, if the source emplacement medium is heavily jointed, the elastic radius could be very large indeed. The possible role of joints is under investigation by several groups (see egn. Heuz´e et al, 1991)

A DAMAGE MECHANICS SOURCE MODEL

The immediate objective of this project is to determine the change in pulse shape associated with the extensive rock fracture which occurs between the hydrodynamic radius and the damage radius (see Fig. 2). Further modification of the pulse caused by amplitude dependent attenuation beyond the damage radius is being investigated by other groups. Which process, if either, is more important remains to be determined.

A complete damage mechanics suitable for incorporation into the numerical codes which simulate underground explosions has two components:

a) A model for the nucleation, growth and interaction of tensile cracks which relates crack length to the applied stress field, and

b) A model for the effective elastic constants as a function of crack length.

Part (a) has been completed and verified by predicting the fracture nucleation and failure surfaces of wide range of rocks as measured in triaxial laboratory experiments (Ashby and Sammis, 1990). We are now focusing our attention on Part (b), which is the main subject of this report.

Before discussing the elastic constants, it is interesting to see how the damage mechanics may be incorporated in the numerical source codes.

1) The current stress-state is used in the equations of motion to calculate displacements, which are used to update the strain field.

2) The elastic constants (which depend on the current state of damage) are used to calculate a new stress field based on the updated strain field.

3) The damage (crack growth) field is updated based on the new stress field.

4) Return to step (1) for another time increment.

Part (a) of the damage mechanics is used in step (3) to calculate the increase in crack growth associated with each change in the stress field. We have this part of the problem in control. Part (b) of the damage mechanics is used in step (2) to calculate the stress field from the strain field. This is the subject of current research.

The difficulty implementing this algorithm is that the elastic constants required in step 2 are not simple functions of the damage, but depend upon whether new damage has been done by the strain increment. The effective elastic constant is less when the cracks are actively extending as illustrated by the stress-strain curve in Fig. 3. At stresses below the fracture initiation stress nonlinear attenuation produces hysteresis in the stress-strain curve but the fracture spectrum remains unchanged. At stresses above the initiation stress the effective elastic modulus is lower when the cracks are growing than when they are simply sliding. The effective elastic modulus during subsequent loadings at the same stress will be larger as illustrated in the figure.

Another problem in modeling the effective elasticity of the damaged rock is caused by the fact that the crack growth associated with a spherical source is largely radial (parallel to the largest principal stress) and this produces an axial elastic anisotropy in each element. We thus have to deal with five elastic constants:

E_r = radial Young's modulus

E_t = transverse Youngs modulus

ν_{rt} = radial - transverse Poisson's ratio

ν_{tr} = transverse - radial Poisson's ratio

G = shear modulus.

The elastic constants can be found from the fracture energy release rate using the following expression:

$$G(L) = \frac{K^2(L)}{E_r(L)} = \frac{p^2}{2b}\frac{\partial C(L)}{\partial L} \qquad (8)$$

where

$G(L)$ = strain energy release rate

L = current crack length

$K_I(L)$ = stress intensity factor

$E_r(L)$ = radial Young's modulus which we seek

$C(L)$ = compliance

b = specimen width

p = load

Referring to Figure 4, we see that $C=u/p$, $p=sA$, $u=eh$, and $E_r=s/e$, so

$$C = \frac{h}{E_r A} \tag{9}$$

Substituting (9) into (8) gives

$$K^2(L) = -\frac{\sigma^2}{2\,b} V \frac{\partial \ln E_r(L)}{\partial L} \tag{10}$$

where $V = hA$ = volume per crack. Integrating (10) gives

$$\ln\left(\frac{E_r(L)}{E_0}\right) = -\frac{2\,b}{V} \int_0^L \frac{K_I^2(L)}{\sigma^2}\, dL \tag{11}$$

The factor 2b/V can be written in terms of the crack density as

$$\frac{2\,b}{V} = 2\, N_V^{2/3}$$

and the crack density N_V can be written in terms of the initial damage D_0 as

$$N_V = \frac{3D_0}{4\,\pi}\left(\frac{1}{\alpha\, a}\right)^3$$

An analytic expression for $K_I(L)$ is given in Ashby and Sammis (1990) which can be directly integrated as in (11) to find $E_r(L)$.

The transverse modulus, E_t, can be estimated using eqn. (4) with

$$K_I = \sigma \sqrt{w \tan\left(\frac{\pi a}{w}\right)}$$

(Tada, 1985) for the transversely loaded array of cracks shown in Fig 5. Integrating in this case gives:

$$E_t = E_0 \exp\left\{ \frac{2 b w^2}{\pi V} \ln\left| \cos\left(\frac{\pi a}{w}\right)\right| \right\} \tag{5}$$

The shear modulus is unaffected by crack growth in this geometry, and the Poisson's ratios can be estimated from the crack opening displacements (which are also functions of the stress intensity factors).

Figure 6 shows the uniaxial stress-strain curve calculated using eqn (11) compared with measurements for Berea Sandstone (This work was done in collaboration with Randy Martin and Xiaoming Tang at New England Research). At low stresses, the negative curvature of the data is caused by the closing of cracks and collapse of pores which are not included in the model. However, the positive curvature of the stress-strain curve near failure is associated with the accumulation of damage and is well modeled, as is the post-failure decrease in strength. Figure 7 shows stress strain curves for the different rock types studied by Ashby and Sammis (1989). Fig. 8 shows the effect of different levels of initial damage on the elastic behavior. Fig. 9 explores the effect of confining pressure, and Fig.10 shows the effect of a fluid in reducing the coefficient of friction on the preexisting fractures. We are currently planning further experiments to test these predictions.

DISCUSSION

The problem of using the damage mechanics model in numerical source simulation codes has been reduced to the problem of finding the stress-strain behavior of a damaged medium. This is not a simple problem because the effective elastic constant (the tangent modulus) is not a simple function of crack damage (as it is, for example, in the Budiansky and O'Connell (1976) low-strain theory) but also depends upon whether an increment in stress produces an increment in crack growth. The problem is further complicated by

anisotropy introduced by the directional (radial) growth of fractures in an explosive stress field. A method has been developed to calculate the effective elastic constants from the stress intensity factors derived by Ashby and Sammis (1990). Preliminary experimental tests of the theory look promising. Efforts are currently underway to build the damage mechanics into existing numerical source simulation codes.

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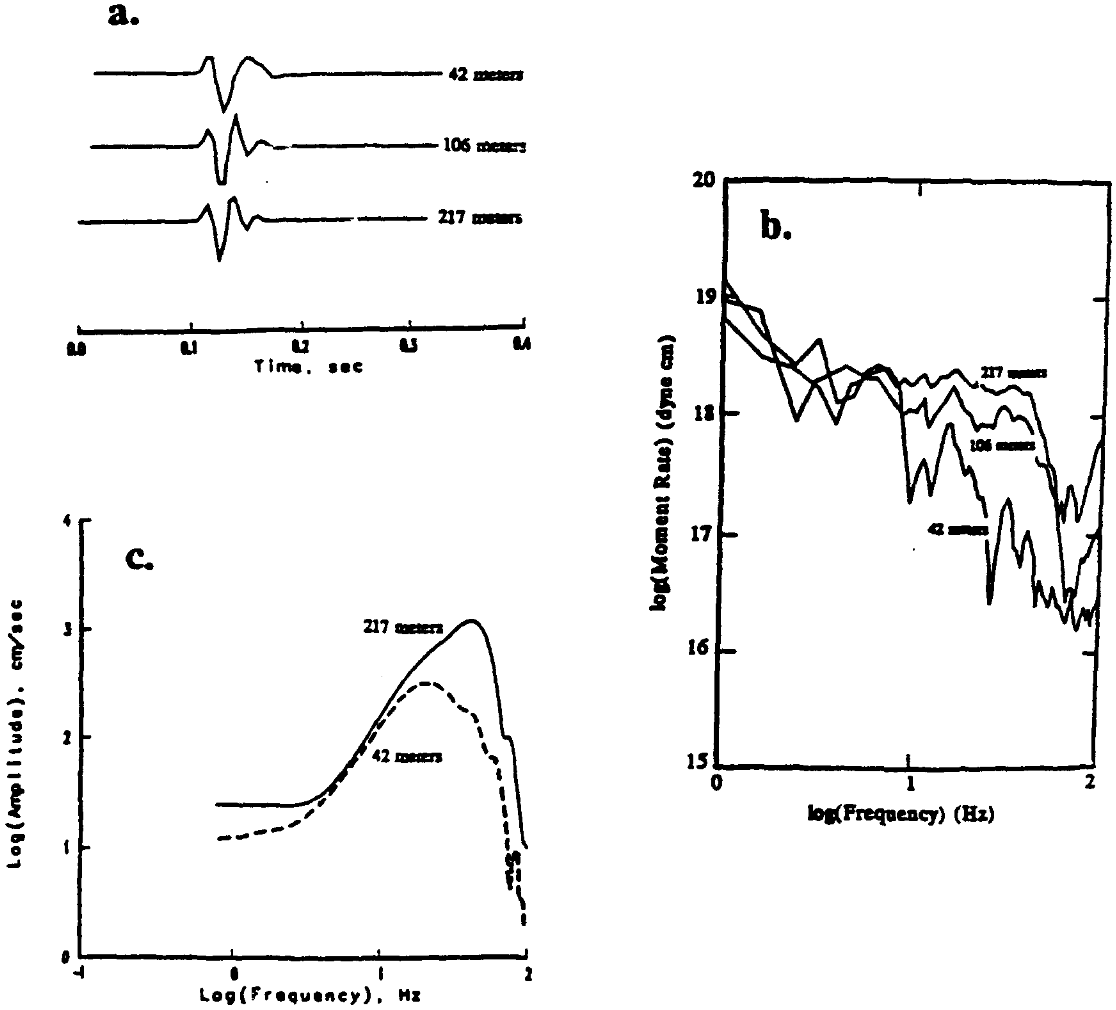

Figure 1. Comparison of three 1000 pound chemical explosions detonated at depths of 42, 106, and 217 meters in a limestone quarry (from McEvilly and Johnson, 1989). Fig. 1a compares the first arrivals on the vertical component at one location. The pulses have been scaled to have the same amplitude. Fig. 1b compares the amplitude densities of the isotropic moment rate tensors for the three events while Fig. 1c gives the amplitude density spectra of the pulses in Fig. 1a.

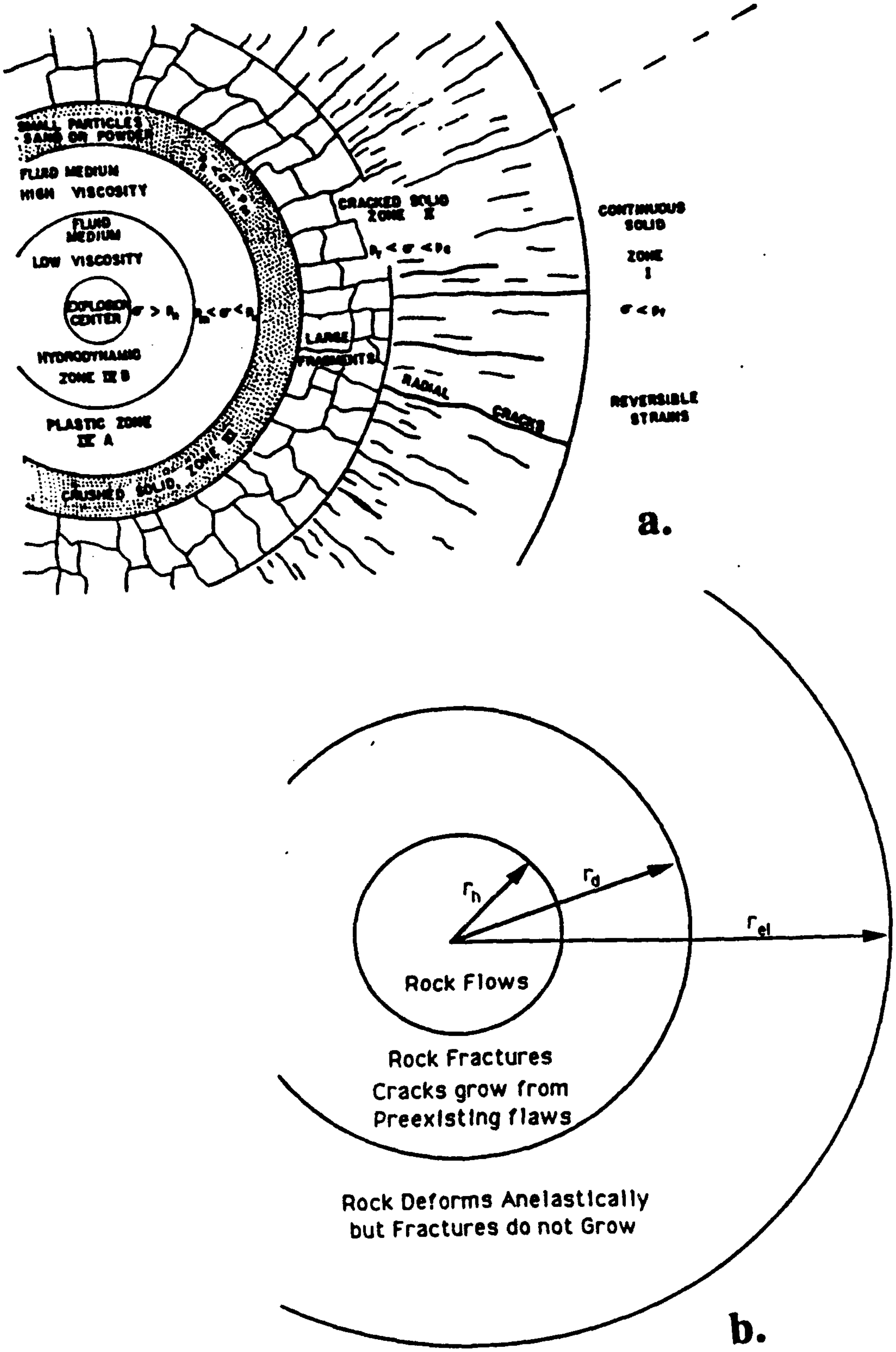

Figure 2. Schematic diagram of the non-linear zones around an underground nuclear explosion. Fig. 2a is from Bishop, 1963. Fig. 2b illustrates the hydrodynamic radius r_h, the damage radius r_d, and the elastic radius r_{el} which are discussed in the text.

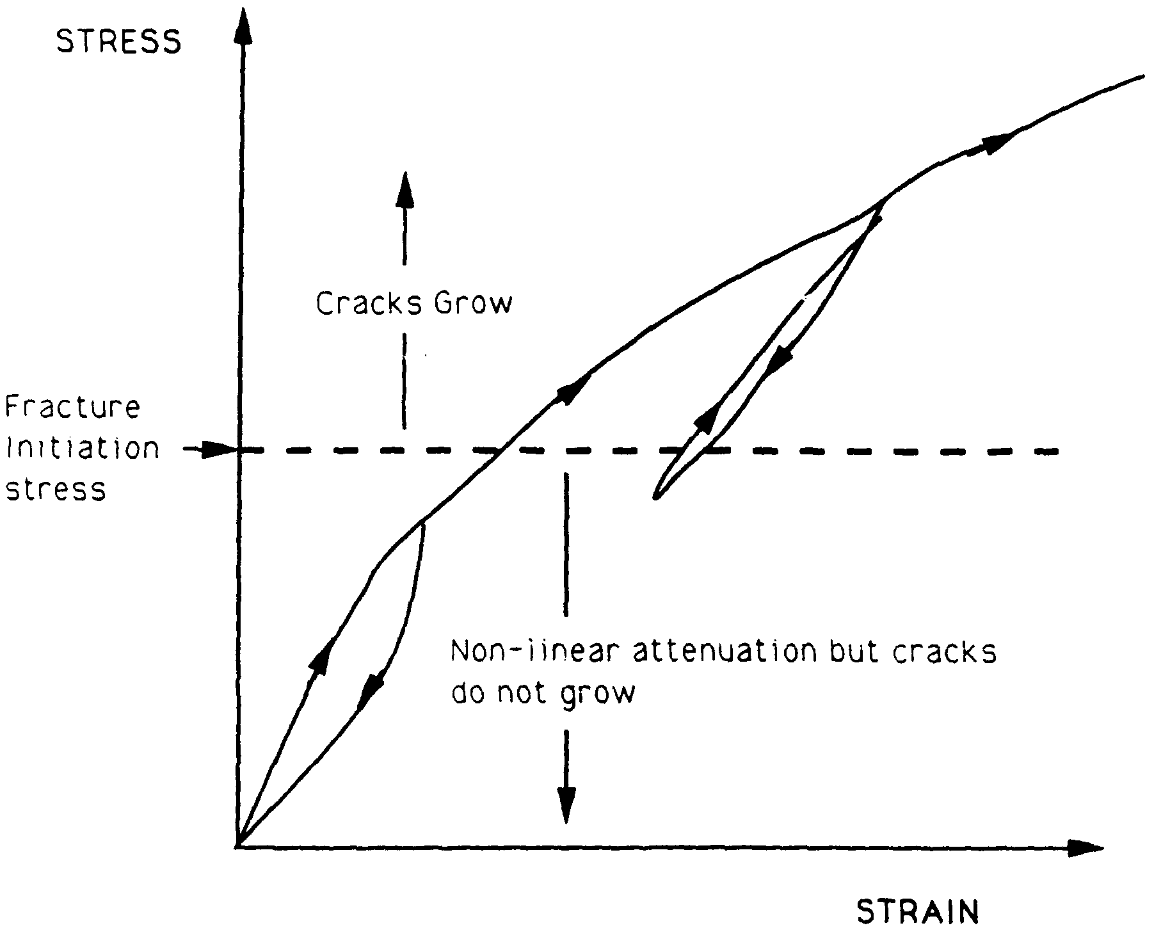

Figure 3. Stress-strain curve illustrating the differences in behavior above and below the fracture initiation stress (which is a function of the current crack damage). At the damage radius r the stresses have fallen below the initiation stress of the preexisting fractures in the emplacement medium.

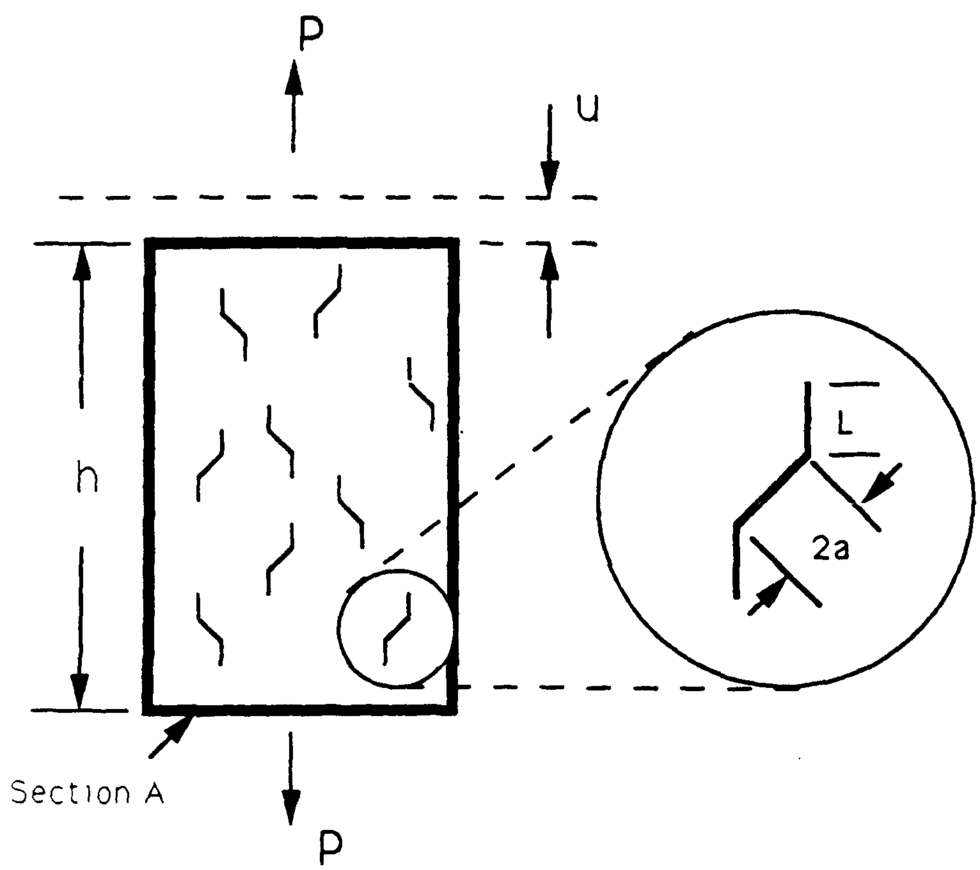

Figure 4. Geometry used to estimate the reduction in the radial Young's modulus associated with crack growth.

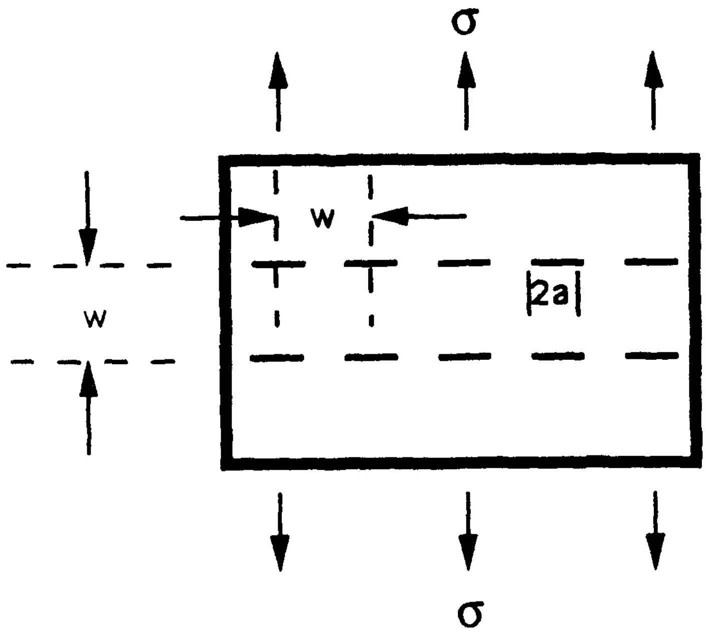

Figure 5. Geometry used to estimate the reduction in the transverse Young's modulus associated with crack growth.

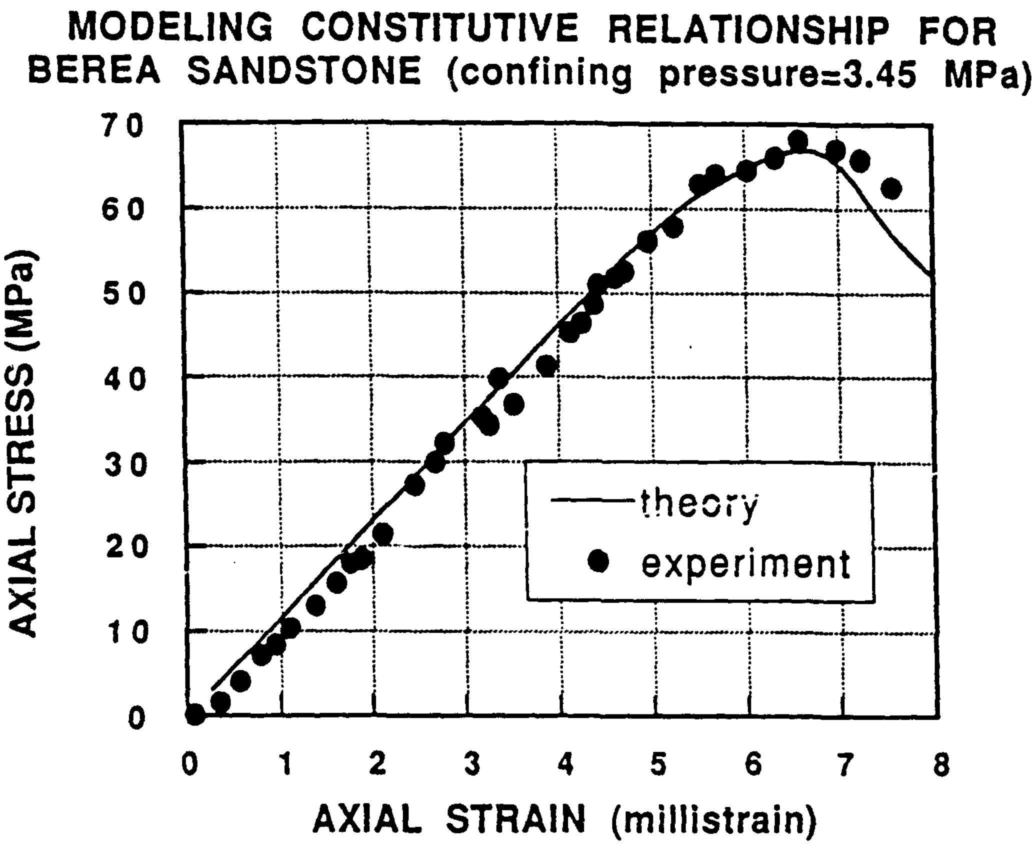

Figure 6. Uniaxial stress-strain curve for Berea sandstone showing a comparison between theory and experiment. Note that the reduction in effective modulus near failure is well modeled.

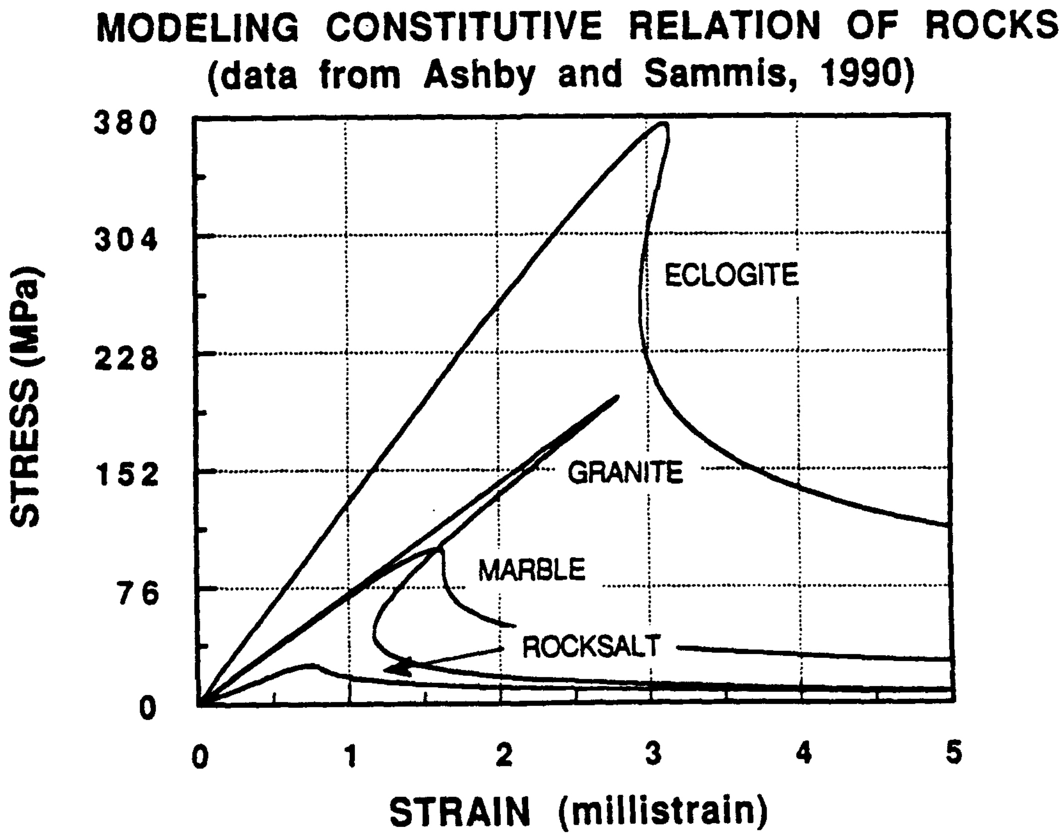

Figure 7. Comparison of the uniaxial stress-strain behavior of the various rock types studied by Ashby and Sammis (1990). Note that the more brittle rocks have a more unstable post-failure regime.

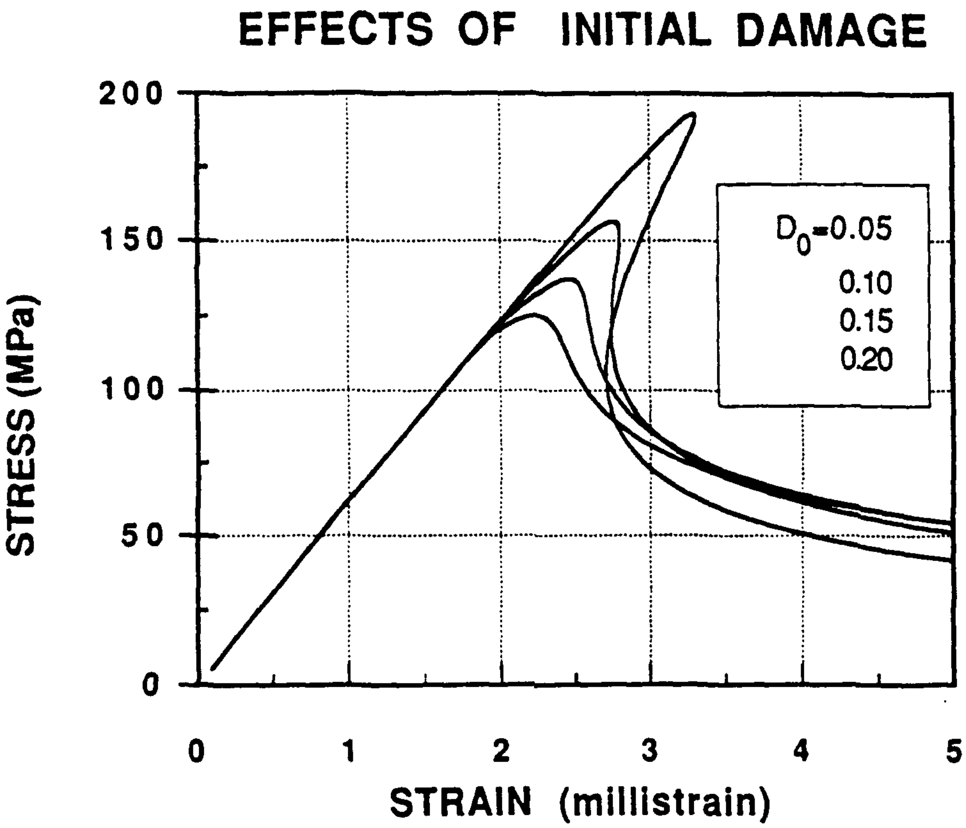

Figure 8. Effect of the initial damage on the uniaxial stress-strain behavior. Note that the strength decreases and the post-failure regime becomes more stable with increasing initial damage.

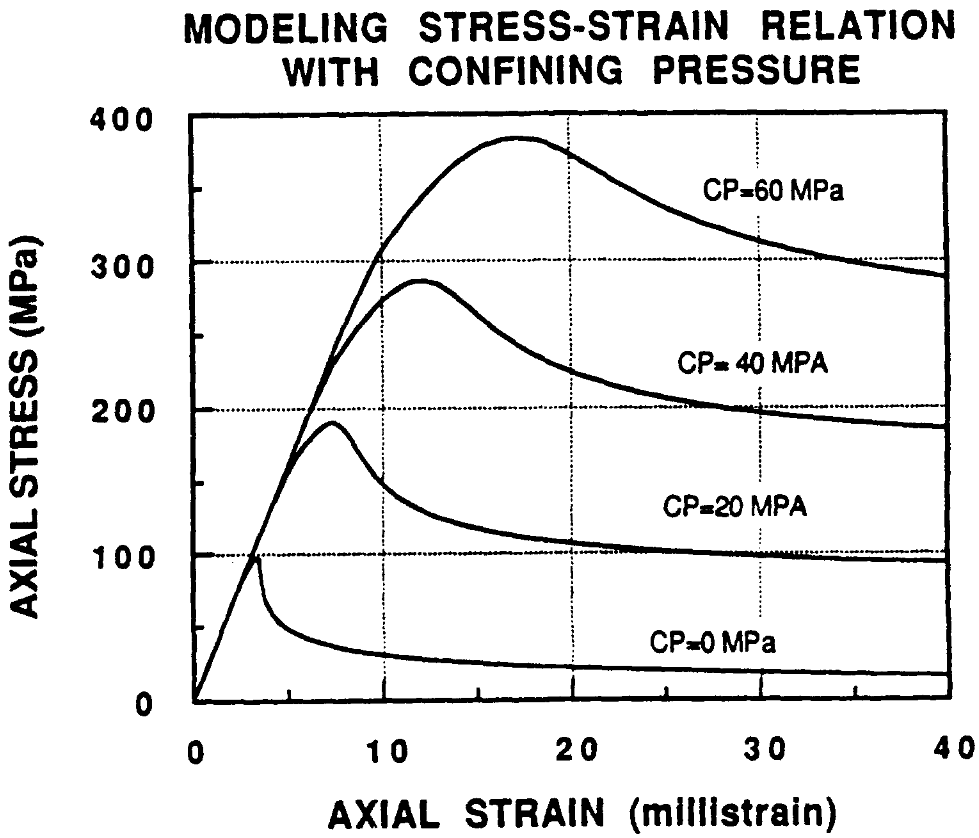

Figure 9. Effect of the confining pressure on the uniaxial stress-strain behavior. Note that the strength increases and the post-failure regime becomes more stable with increasing confining pressure.

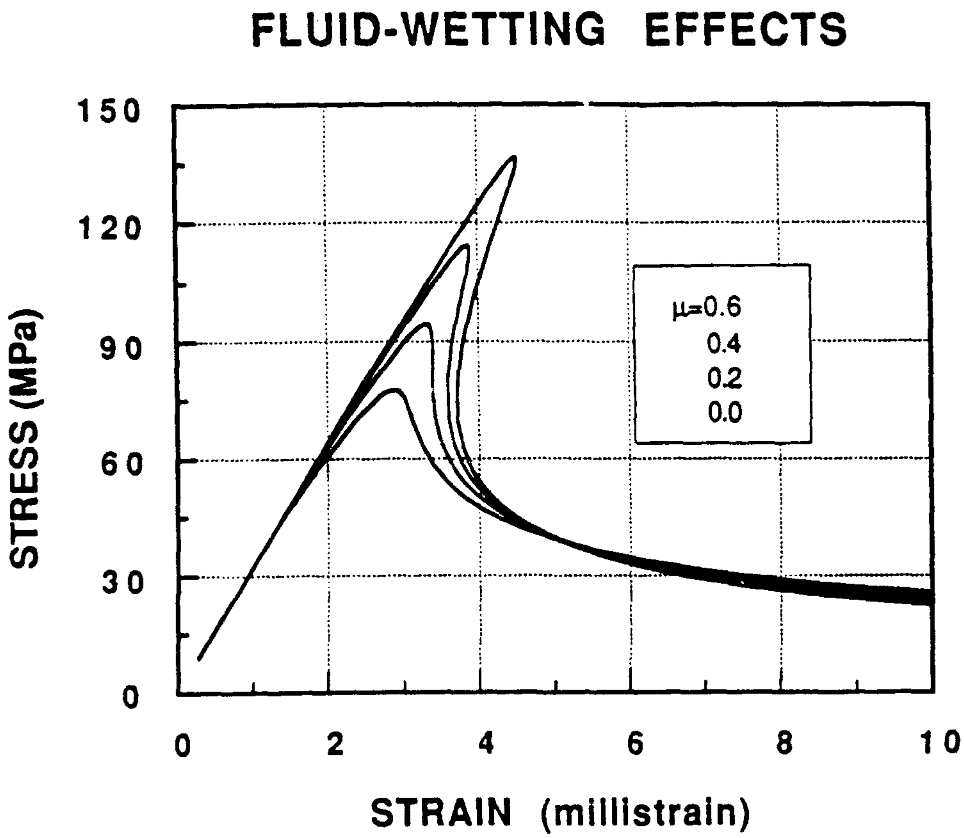

Figure 10. Effect of the fluid-wetting of the preexisting flaws on the uniaxial stress-strain behavior. Note that the strength decreases and the post-failure regime becomes more stable as the coefficient of the friction μ is reduced by wetting.

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